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Monte Carlo simulations of the response of a plastic scintillator and an HPGe spectrometer in coincidence

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ABSTRACT

A simulation programme based on the Geant4 toolkit has been developed to simulate the coincident responses of a plastic scintillator and an HPGe detector to the cosmic-ray muons. The detectors are situated in a low-level underground laboratory (25 m.w.e). Primary positions, momentum directions and energies of the muons are sampled from the angular and energy distributions of the cosmic-ray muons at the shallow underground level. Obtained coincident spectra of both detectors are presented and discussed.

1. Introduction

The Low-Background Nuclear Physics Laboratory at the Institute of Physics in Belgrade has an underground facility with a 12 m of earth overburden, what amounts to approximately 25 m.w.e. This overburden absorbs practically the cosmic-ray nucleonic component and reduces the cosmic-ray muon flux up to four times (Antanasijevic et al., 1999). One coaxial HPGe detector (ORTEC, type GEM30) operates in the laboratory; its active volume is 148.9 cm^3 and relative efficiency 35%. The underground position of the detector, together with a 12 cm passive lead shield (old lead which ^{210}Pb specific activity is 25 Bq/kg), yields a good background reduction, with a count rate of less than 0.5 s^{-1} in the 40–3000 keV range. However, some cosmic-ray induced background still remains, which originates from the muons and the secondary particles induced by the muons in the surrounding materials, especially the lead shield; that can be further suppressed by an active veto shielding. The Low-Background Laboratory possesses two identical plastic scintillation detectors (manufactured by Amcrys-H, Ukraine), dedicated to the continuous monitoring of the cosmic-ray muon intensity at both the ground and the underground levels. The scintillation detector in the underground laboratory is placed above the HPGe spectrometer (at 0.44 m distance from the lead shield) and will be used as the active shield. It has dimensions $1\,m \times 1\,m \times 0.05\,m$ and the material characteristics are as those of the scintillation material NE102A. Four photomultiplier tubes are placed at the corners of the scintillation detector and each PM tube collects scintillation light from the scintillator volume. The signals from the PM tubes will then be digitized via the 4-channel flash ADC (C.A.E.N., model N1728B) and stored as event files on a PC. The raw events data can be analyzed off-line. Besides four standard channels, the ADC allows up to four extra input channels. Using one of them as an input for the signals from the HPGe spectrometer, and with proper selection criteria, the scintillator-HPGe coincidence/anticoincidence events can be obtained from the list of all events. However, acquisition of the digitizer module is still under way and the measurements with the veto system did not start yet.

Prior to experimental measurements, and as a part of the preliminary feasibility study for the whole anti-cosmic veto system, Monte Carlo simulations of the coincident responses of the plastic scintillator and the HPGe detector, based on the Geant4 package (Agostinelli et al., 2003), have been made. Once the system is completed we shall compare the predictions of the MC simulations with experiment. By this, the simulation code can be validated. If it would be shown that the experimental results are in good agreement with the simulation data, the same simulation programme can be used to obtain muon induced background in the lead shield of the germanium spectrometer.

2. Simulation code

The Geant4 simulation package is a development environment for fast and accurate Monte Carlo simulations of the passage of

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particles through matter. It contains complete toolkit for modeling the particle trajectories and interactions: definition of the detector geometry and materials, implementation of the particles and physical processes, and generation of the primary events, particle trajectories and detector response. This makes Geant4 good and flexible for wide range of applications in high energy, nuclear and accelerator physics, as well as studies in medical and space science. In this simulation version 9.0 of Geant4 has been used.

First, the two-detector system geometry has been constructed by defining detectors' shapes, materials which they are made of and their mutual positions. The HPGe detector, along with the additional assembly, is constructed according to manufacturer's data sheet. The detector is of a cylindrical shape with a diameter of 58.5 mm and a length of 56.4 mm. The inner detector hole has a diameter of 9.0 mm and a length of 42.9 mm. The inactive germanium layer is 0.7 mm thick. The copper holder has a length of 94 mm and is 0.76 mm thick. All are mounted in the magnesium cap which has a length of 120 mm, a diameter of 65 mm and a thickness of 1.5 mm; endcap-to-crystal gap is 3 mm. It is not necessary to construct detector in such detail, since the relevant parameter is the detector diameter/height ratio, which is different for different detectors, even of same efficiency. However, since other parameters are known, it seems proper to take care of them. Additionally, it is of a great importance for some other MC simulations to take care of accurate parameters. The whole detector assembly is placed inside 12 cm thick lead shield, at the position of 10 cm below the upper side of the shield. The plastic scintillator is placed at 0.44 m distance above the lead shield. It has a prismatic shape with dimensions $1\,\mathrm{m}\times 1\,\mathrm{m}\times 0.05\,\mathrm{m}$; the scintillation material is a polymer with H/C ratio 1.1 and density $1032\,\mathrm{kg/m^3}$. The detector geometry is shown in Fig. 1.

Primary events in the simulations are generated by defining an incident particle, its position, momentum direction and energy. The incident particles are positive or negative muons, knowing that a ratio of number of the positive to number of the negative muons is 1.3 (there are 1.3 times more positive than negative muons) (Grieder, 2001a, b). The initial positions of the muons are sampled on the surface of the plastic scintillator, on the upper

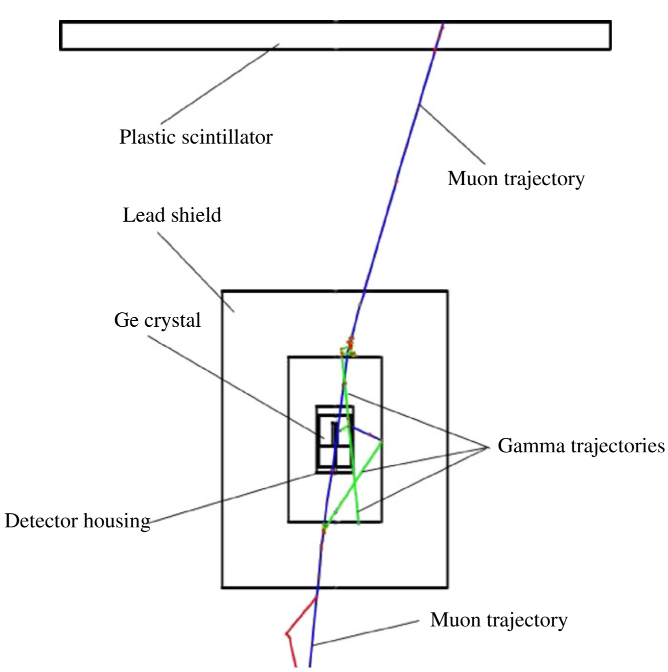

Fig. 1. Detector geometry and visualization of one simulated event.

horizontal side and four vertical sides (or, due to symmetry, on only one vertical side with four times higher probability). The cosmic-ray intensity depends on zenith angle following the law:

$$I(\theta) = I(0)\cdot\cos^n\theta \tag{1}$$

where n has value 1.85 at sea (ground) level and 1.55 at 12 m underground level (Miyake, 1973; Grieder, 2001a, b). Muons with the $\cos^n\Theta$ angular distribution contribute to muon flux through the horizontal detector surface:

$$\begin{aligned} J_{1H} &= \int_{\Omega_1} I(\theta)\cdot\cos\theta\cdot\sin\theta\cdot d\theta\, d\varphi \\ &= 2\pi\cdot I(0)\cdot\int_0^{\pi/2}\cos^{(n+1)}\theta\cdot\sin\theta\cdot d\theta\, d\varphi \\ &= 2\pi\cdot I(0)\cdot\frac{1}{n+2} \end{aligned} \tag{2}$$

where Ω_1 is the upper hemisphere, and also to muon flux through the vertical surfaces

$$\begin{aligned} J_{1V} &= \int_{\Omega_2} I(\theta)\cdot\sin^2\theta\cdot\cos\varphi\cdot d\theta\, d\varphi \\ &= \int_{\Omega_2} I(0)\cdot\cos^n\theta\cdot\sin^2\theta\cdot\cos\varphi\cdot d\theta\, d\varphi \end{aligned} \tag{3}$$

where Ω_2 is a quarter of the sphere. From the ratio of horizontal and vertical probabilities (Eqs. (2) and (3)) follows that muon flux through unit horizontal surface is 3.64 times higher than muon flux through unit vertical surface (Dragić et al., 2008). Since the horizontal side of the scintillator has an area of $1\,\mathrm{m}^2$ and four vertical sides have an area of $0.2\,\mathrm{m}^2$, one can conclude that a cosmic-ray muon has in total 18.2 higher probability to hit the horizontal side of the detector. Hence, the primary muon positions are sampled in two steps: first, using this probability, the horizontal or the vertical side of the detector is chosen, and then the muon coordinates on the chosen side are sampled from uniform distribution. The primary momentum directions of the incident muons are sampled from $\cos^{1.55}\Theta$ directional distribution. Energy of the muons, E_μ, is derived from the energy distribution at sea level

$$\frac{dj_\mu(E_\mu,\cos\Theta)}{dE_\mu} \approx 0.14E_\mu^{-2.7}\left(\frac{1}{1+\frac{1.1E_\mu\cos\Theta}{115}}+\frac{0.054}{1+\frac{1.1E_\mu\cos\Theta}{850}}\right) \tag{4}$$

(Gaisser, 1990), where E_μ is in GeV and $\cos\Theta$ is sampled from $\cos^{1.85}\Theta$ distribution, in a way that only those muons that survive interaction with 12 m thick rock are taken into consideration.

Physics is implemented in the simulation through the QGSP physics list, which incorporates all relevant processes leading to production of secondary particles by muons, as well as to contribution to energy loss in the detectors. The processes include electromagnetic interactions of muons, electrons, positrons and gammas, nuclear interaction of muons with nuclei and hadronic interactions of secondary particles. Detailed information on the QGSP physics list may be found at the Geant4 web: http://geant4.web.cern.ch/geant4/support/proc_mod_catalog/physics_lists/hadronic/QGSP.html.

3. Results and conclusion

The first goal of the simulations is to obtain the spectral responses of the germanium spectrometer and of the plastic scintillator, to the incoming muons and the muon-induced particles, in other words to find a distribution of the number of counts as a function of the energy deposited in each detector. As mentioned, only muons that pass through the scintillator contribute to the spectrum. This narrows a solid angle from which the muons hit the lead shield and the germanium detector.

In experiment, that would be those events that are registered in the active shield.

Total number of simulated events is 1.5×10^8, which can be associated to the live time of experimental measurements. The cosmic-ray muon flux in the underground laboratory has been previously measured and is found to be $45(2)\,\mathrm{m^{-2}\,s^{-1}}$ (Dragić et al., 2008). As the effective area of the scintillator surface is $1.055\,\mathrm{m^2}$, 1.5×10^8 events correspond approximately to 3.2×10^6 s ($\approx$37 days) of live time. The number of recorded coincidences that follow from this arrangement is 623 400. The obtained coincident spectra of the scintillation detector and the HPGe detector are presented in Figs. 2 and 3. Detector resolutions are not taken in account in the simulation. For each spectrum data are plotted in 1000 bins.

In experimental measurements a threshold on the scintillator would be set so to correspond to energy of 6 MeV, which is beyond ambient gamma energies and also separate muon events from ambient radiation events. However, the simulated spectrum of the scintillator shows that there is a small percentage of coincident events below 6 MeV threshold (less than 4%), which means that in the experiment some of the events would be lost.

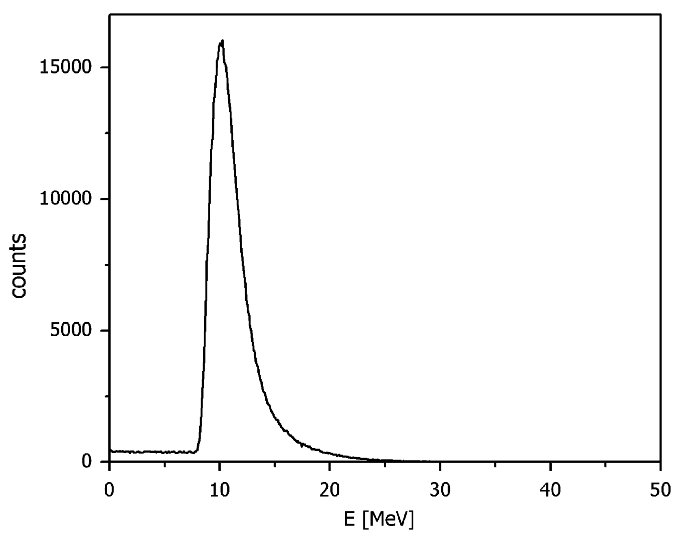

Fig. 2. Coincident spectrum of the plastic scintillator.

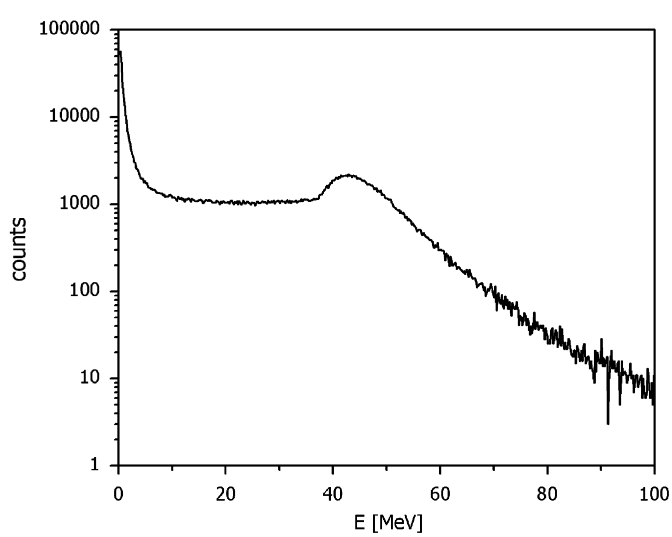

Fig. 3. Coincident spectrum of the HPGe detector in interval 0–100 MeV (interval 100–200 MeV is of no interest as the spectrum falls towards 0 counts).

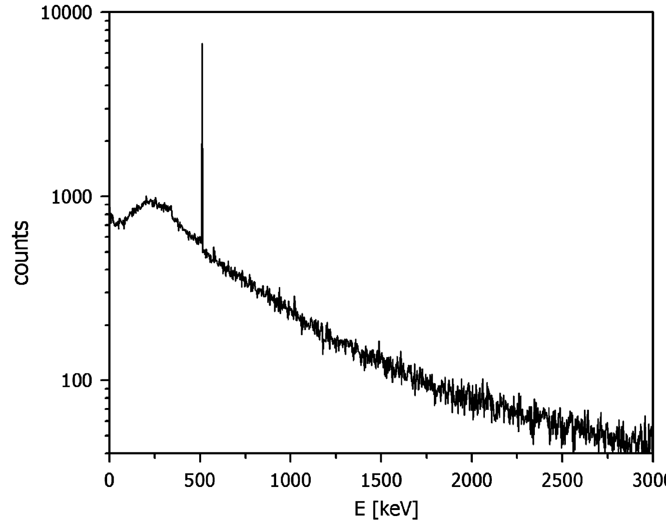

Fig. 4. Coincident spectrum of the HPGe detector in interval 0–3000 keV.

The simulated spectrum of the germanium detector stretches up to 200 MeV. The high-energy part of the spectrum is due to muon energy deposit when muons directly hit and pass through the detector. It is almost flat from 8 to 37 MeV and has a broad peak around 43 MeV. The low-energy part of the spectrum (below 5–6 MeV) is mainly due to energy deposit of particles induced by muons in the surrounding materials. It is partially (interval 0–3000 keV) presented in Fig. 4. As expected, it is continuous at higher energies and has an annihilation peak at 511 keV. Also, there is a bump at around 200 keV, which is mainly contributed by bremsstrahlung in the lead shield. Integral count in 0–3000 keV energy range of the coincident spectrum of the HPGe detector is 260 800; the predicted count rate would thus be $0.081(4)\,\mathrm{s^{-1}}$. The count in the annihilation peak is found to be 6800, and its count rate is $0.0021(1)\,\mathrm{s^{-1}}$.

The results are compared with the Geant4 simulation of muon-induced background in the lead shield of the HPGe spectrometer. The number of the simulated events is chosen to correspond roughly to the number of the events in the previous simulation (corresponding to the equal live time of 3.2×10^6 s). (Effective area of the lead shield is $0.3232\,\mathrm{m^2}$ and with the cosmic-ray muon flux of $45(2)\,\mathrm{m^{-2}\,s^{-1}}$, there are 4.65×10^7 events.) The obtained response of the detector, in the 0–3000 keV energy range, is shown in Fig. 5. Integral count in this range is 566 000, and the count rate is $0.177(8)\,\mathrm{s^{-1}}$. Comparing the two results, it follows that our current experimental veto set-up would almost half the contribution of cosmic-ray muons to the germanium background spectrum, which we, having in mind covered solid angle, consider rather satisfactory.

However, this does not make a great improvement of the background reduction, since the integral count rate in 0–3000 keV will decrease only 15% (to $0.40–0.42\,\mathrm{s^{-1}}$). If the scintillator is placed closer to the lead shield and with additional scintillators at the sides, the background count rate can be further decreased to $\approx0.3\,\mathrm{s^{-1}}$. The background lower than this can be achieved by reducing its main sources: ^{222}Rn and its progeny, ^{210}Pb in the lead shield, radioactivity in the construction material of the detector, or cosmic-ray-induced neutrons in the rock. Radon activity is kept at $15\,\mathrm{Bq/m^3}$ using ventilation system which provides 200 Pa higher air pressure in the laboratory than atmospheric pressure. As an efficient way to suppress radon induced background of the HPGe, flushing of nitrogen evaporating from the Dewar vessel inside the lead shield will be used. The ^{210}Pb characteristic X-ray lines can be reduced or eliminated by adding a layer of electrolytic

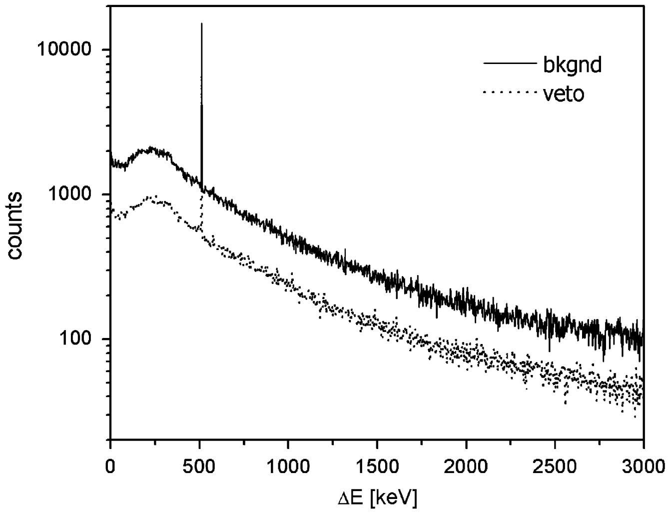

Fig. 5. Background induced by muons in the lead shield of the HPGe detector, with estimated veto reduction.

Cu (~1 cm) on the inner side of the lead shield. This can, however, increase the background at energies above 300 keV. Usually, an additional thin layer of Sn is used to eliminate this increment.

Acknowledgment

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